Inverse Problems in Optical Remote Sensing of Coastal Waters

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LONG-TERM GOALS

The long-term goal of the Project is to develop robust inversion algorithms to extract estimates of the optical and physical properties of sea water layers, the sea floor, and the sea surface from LIDAR (Light Detection and Ranging) returns, and optical imagery of the ocean bottom and depths and to improve the quality of images of subsurface objects collected over the sea.

OBJECTIVES

The project objectives are: 1) to develop new models of water, bottom, and surface returned LIDAR signals and to develop new mathematical inverse techniques to extract from actual or simulated LIDAR returns the inherent optical properties of water (IOP) and to estimate parameters of internal waves (IW) from IW-induced disturbances of IOP stratification; 2) to develop theoretical mathematical techniques and experimental procedures to improve the quality of passive images of the coastal sea floor by correcting distortion due to light refraction through rough sea surfaces; and 3) to develop mathematical techniques for the retrieval of the quantity of optically active materials (chlorophyll, dissolved organic matter, and sediment) from the color spectrum of sea water optical returns.

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APPROACH

The project is broken into three tasks: 1) the determination of IOP**s** of sea water and parameters of IW using LIDAR soundings; 2) the correction of surface wave refractive distortion; and 3) the estimate of optically active material (OAM) content from the spectrum of returned light.

Our approach in accomplishing the first task, i.e. the determination of IOPs and physical properties of sea water using LIDAR soundings, is to improve IOP estimation from LIDAR returns by using correlations between various IOPs and by jointly processing the signals from two or more sensors with different viewing angles. Specifically algorithms will be developed to determine difficult-to-measure IOPs from easily measured IOPs by taking advantage of observed IOP correlations. The accuracy of these algorithms will then be evaluated. Other algorithms not using IOP correlations will be developed to independently determine the backscattering and scattering coefficients using signals from several sensors. Mathematical models of LIDAR images of the internal waves will also be developed. The basis for this development is given in Dolina et al. (2005). Using known LIDAR signal equations and analytical models of internal waves, a model and an algorithm for numerically modeling the IW-induced LIDAR image generated by several lower order IW modes will be developed. These will be used to analyze the possible methods to solve the inverse problem and determine the IW parameters from their LIDAR images.

Our approach in accomplishing the second task, i.e. the correction of surface wave refractive distortion, follows the theory developed and described in Gilbert et al. (2006). Here the mathematical background for the image transfer through a rough sea surface under natural illumination is presented as the basis of an advanced sea bottom imaging model. This model may be used to choose a flight strategy (e.g. direction with respect to waves and sun, etc.) to decrease the image distortion caused by waves. However even the best flight strategy can only mitigate, but not completely remove sea surface wave caused image distortion. Thus we are going to develop a method to correct wave-induced distortion in images of the coastal sea bottom. Our method will involve obtaining surface slope information from multispectral surface images and then developing algorithms that use the full information about two-dimensional anisotropic surface roughness to correct bottom images. Methods will also be developed to correct image distortion when only partial information about sea surface relief and slope is available. We will analyze image retrieval quality as a function of the completeness of the amount of surface relief information. The basis for this research is given in Dolin et al. (2003, 2004, and 2005). Laboratory equipment will be built and experiments conducted on the retrieval of images distorted by surface waves. The experiments will use synchronously registered images of a test object and of surface light glitter while measuring the wave amplitude distribution within the surface area responsible for the image distortion.

Our approach in accomplishing the third task, i.e. the estimate of optically active materials (OAM) content from the spectrum of returned light, is to develop an algorithm computing the best linear estimate of OAM, e.g. phytoplankton, sediment and yellow substance, from radiance spectra measured by multi- or hyperspectral sensors located at arbitrary height above the sea surface. This algorithm will also account for sensor noise and maritime atmospheric variations. Earlier versions of this approach are presented in Levin et al. (2005). The accuracy of OAM retrieval will be estimated and an analysis will be made of possible ways to increase retrieval accuracy by varying sensor parameters and expanding a priori information about observational conditions.

WORK COMPLETED

Work completed for the first task, i.e. the determination of IOPs of sea water and parameters of IW using LIDAR soundings, has been the development and testing of an algorithm for the computer simulation of a bi-modal IW field using real vertical distributions of seawater density and optical attenuation coefficient. The distinctive properties of the first and second mode images have been established. The effect of light absorption and forward scattering on the IW image parameters has been analyzed and a simplified image model was suggested which ignores their non-essential consequences. The possibility was demonstrated to use this model for the solution of the inverse problem, i.e. the determination of the IW parameters from its lidar image.

The second task treated the correction of the refractive distortion in an image due to surface waves. Work completed included a laboratory experiment performed using a new experimental technique developed and constructed during the first stage of the project. The laboratory-modeling installation (LMI) was designed and fabricated to experimentally investigate light and image transfer through wavy water surfaces. The LMI was equipped with a color digital camera which simultaneously obtained a green image of a self-luminous black and white striped underwater test object and a glitter pattern of the surface which was illuminated by a parallel red beam of light. The resulting photographs were taken with a 1/400 second exposure time. If the geometry of an experiment is known and stable, a glitter pattern may be processed to obtain the value of the surface slopes in the vicinity of the specular points within the area of water's surface producing image distortion. Thus for each instantaneous image the glitter slope information was used to correct the distorted image by moving an element of distorted image to the point into which this element would be projected if it had been refracted through a flat surface. Thus after processing a single instantaneous photograph we obtain a quite sharp image over a portion of the scene viewed. By repeating this processing procedure for a rapid sequence of many photographs of the scene (about 300 in our experiment) and accumulating them, the sequence of sharp partial images builds into a final relatively undistorted image of the entire scene. The result is that the restored image of the distorted object is quite close to the initial undistorted image. As sea surface distortion causes rays from many different points of the object to arrive at one point in the image plane, the processing algorithm selects only the elements with maximum intensity, ignoring the rest. This procedure produces the homogeneity of the stripes seen in the reconstructed image.

The third task used the spectrum of returned light to estimate the content of optically active materials (OAM). We developed a computer code and computed linear regression coefficients to retrieve concentrations of in-situ materials and the residual variance of OAM concentrations estimated from measured spectra. The computations were made for a hyperspectral sensor at an arbitrary altitude over the sea surface. The code was based on a new simple optical model of the maritime atmosphere and accounted for shot and dark-current noise. To compute the statistical moments of joint distributions of OAM concentration and spectra registered by sensor, one thousand water samples were created for Monte Carlo modeling. The sample set was created by randomly sampling the distributions of OAM concentrations as well as the wind velocity, solar zenith angle and some parameters of atmosphere. Additionally a number of the most recent optical models of seawater were tested during comparative computations.

RESULTS

For the first task, the study of IW lidar signals, it was immediately obvious that any algorithm for modeling lidar images of IWs requires analytical models of IW dynamics. Such an analytic model

must accurately account for the nature of the specific hydrological conditions in the given Ocean region. It was shown that the Gren model (Gossard and Hooke, 1975) may be used for modeling multi-mode IW fields in the Barents Sea.

A comparative analysis of the lidar images of the first and the second IW modes has shown that the difference between them is mainly due to their different wavelengths at a given frequency (Fig. 1). The vertical structures of the corresponding images for the two modes differ strongly as well. The first mode's influence on the vertical distribution of the attenuation coefficient $c(z)$ in the region of the pycnocline appears mainly as a vertical shift of this distribution up or down without substantially changing its shape. However the second mode essentially changes the shape of the $c(z)$ profile since it shifts the liquid volume elements above and below the pycnocline's horizontal axis to opposite sides of the axis. This difference between the first and second mode disturbance of the $c(z)$ profile appears distinctly in the structure of the lidar images, and thus can be used to determine the mode composition of the IW field.

It was shown that the lidar image of IW consists of two components, one carrying information about local disturbances of the backscattering coefficient profile by the IW, while the other records the vertical disturbances of the optical depth of the water layer through which the laser pulse passes. Disturbances in the optical depth appearing in the return signal from the water body with homogeneous (or almost homogeneous) IOP, which is placed under pycnocline, indicates a horizontal IW modulation. This modulation appears as shadow structures, i.e. the bands in power at the deeper depths seen in the top panel in Fig.1, which are projected images of the IW.

An analysis of the mechanics of the IW projection image shows it to mainly be due to disturbances of the distribution of an effective absorption coefficient defined as the sum of the absorption coefficient plus twice the backscattering coefficient. Disturbances in the distributions of the forward scattering coefficient weakly appear in the IW image. Ignoring this very small forward scattering disturbance and using known correlations between different IOPs, we have derived a very simple equation which relates the relative variations of the return signal power (δP) to disturbances of the attenuation coefficient profile (δc) in the IW field. This equation has been used to derive formulae to determine the spatial distribution $\delta c(x,z)$ from the measured disturbances of the return signal (δP). This formulae as well as an equation relating $\delta c(x,z)$ to the field of the IW vertical fluid displacements (ς) served as the basis for an algorithm which retrieves the field ς from an IW lidar image. Operation of the algorithm has been demonstrated on the modeled signals.

The second task was concerned with correcting image distortion due to refractive effects of a wavy sea surface. Some results are shown in Fig.2. The left box (A) shows the test-object image obtained through a flat calm water surface. The furthest right box (C) is an image of the same test-object obtained through a wavy air-water interface with an exposure time of 1/400 s. As may be seen, the image is highly distorted with almost no apparent information about the spatial structure of the original test-object. The central picture (B) shows the corrected image after using our image processing method on about 300 images. As may be seen the restored image is very close to the undistorted initial test-object image.

Although the procedures of the laboratory experiment can't be immediately applied to observations through a real wavy sea surface the possibility has been demonstrated for correcting images of

underwater objects distorted by the waves. It also suggests important issues that must be considered if and when an in situ experiment is planned.

Task 3 was concerned with the estimation of the content of optically active materials (OAM) in a water volume from the spectrum of remotely sensed returned light. A major result has been the development of a method to compute the best linear estimate of concentrations and the retrieval accuracy from spectral measurements while accounting for sensor noise. Our computations show that shot and dark-current noise must be accounted for to give a much more realistic estimate of retrieval accuracy. In principle accuracy can be improved by collecting more photons by increasing the sensor aperture and observation time. A number of seawater optical models were tested, and retrieval results were robust to the choice of model used in simulations. Computations showed that an atmosphere layer noticeably worsened the accuracy of a concentration's retrieval and that the relative errors in phytoplankton concentration estimation are significantly greater than the corresponding errors for sediments and yellow substances.

Fig.3 illustrates the dependence of retrieval accuracy given as percentage relative error on the sensor height H . The sensor for which the computations were done was the Littoral Airborne Sensor/Hyperspectral (LASH) pushbroom imaging sensor developed by the former Science and Technology, Inc. of Honolulu, Hawaii. In the figure the concentrations of phytoplankton, sediment and yellow substances are denoted by C, X, and Y respectively. One can see that the atmosphere mainly affects accuracy when the sensor is in the atmospheric layer about 5 km above the sea surface.

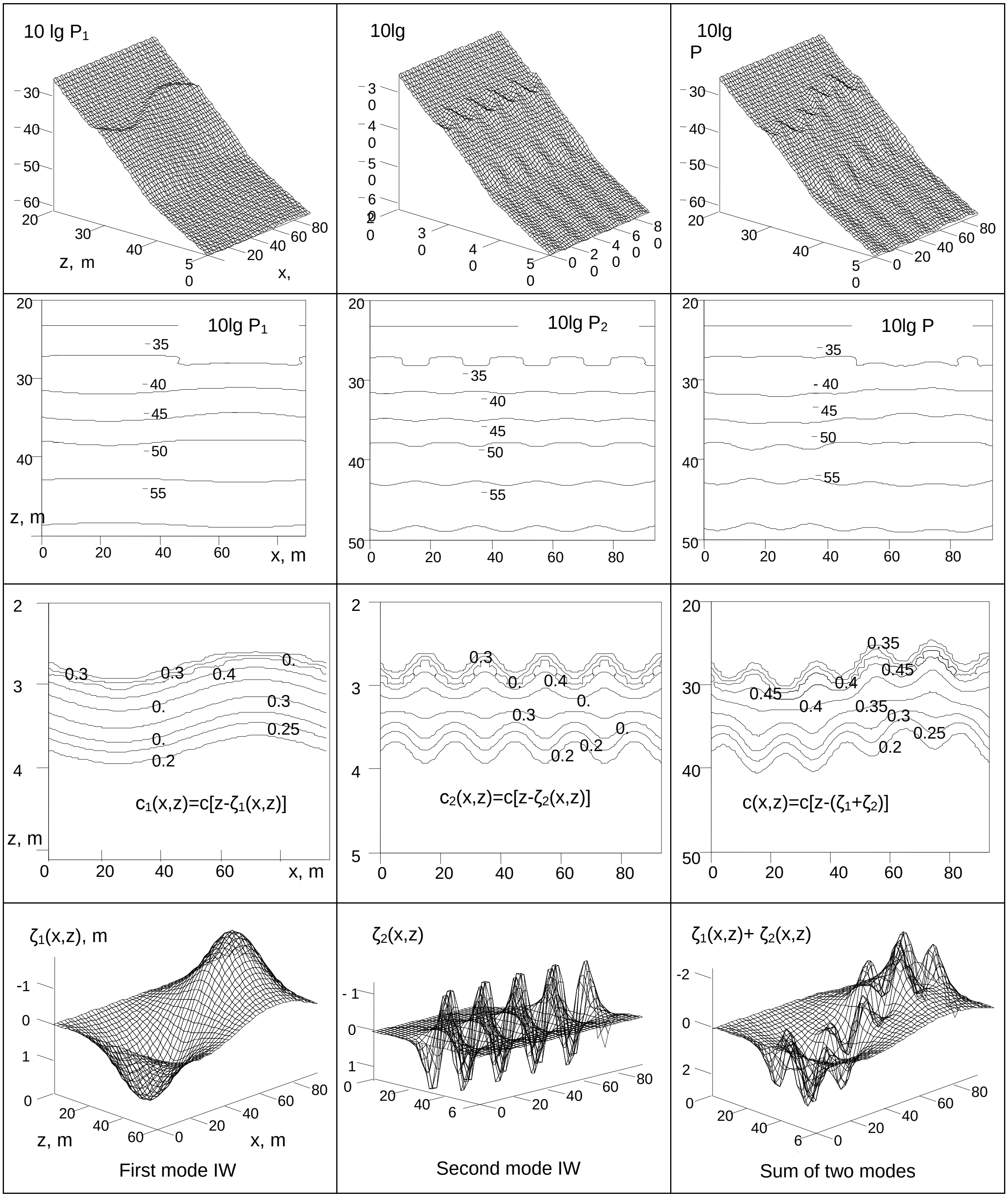


Figure 1. The bottom panel shows the surface plots of the vertical displacement ς of fluid element with coordinates x,z under the action of internal wave (IW) for the first, the second and the sum of two IW modes; the second panel from the bottom shows contour plots of the spatial distribution of attenuation coefficient c(x,z) disturbed by these IW ; the two top panels show the surface and contour plots of the function 10log P(x,z), where P is the returned signal power in watts.

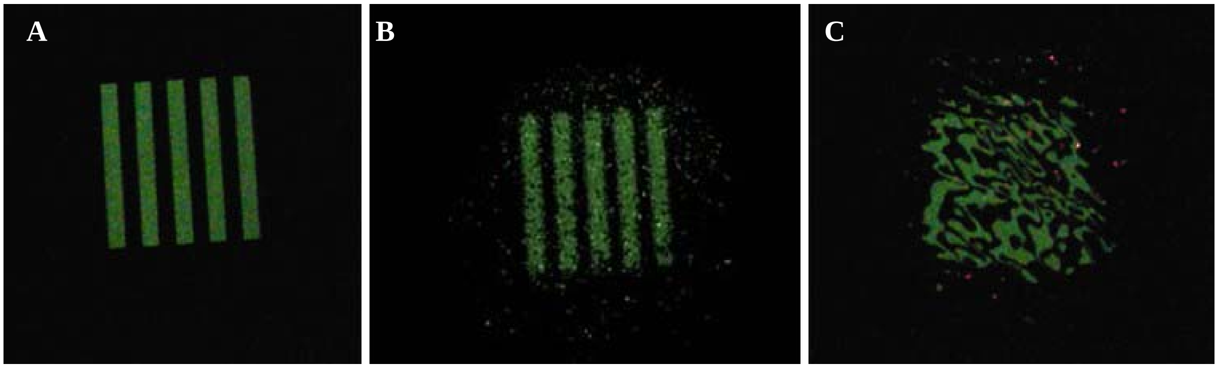
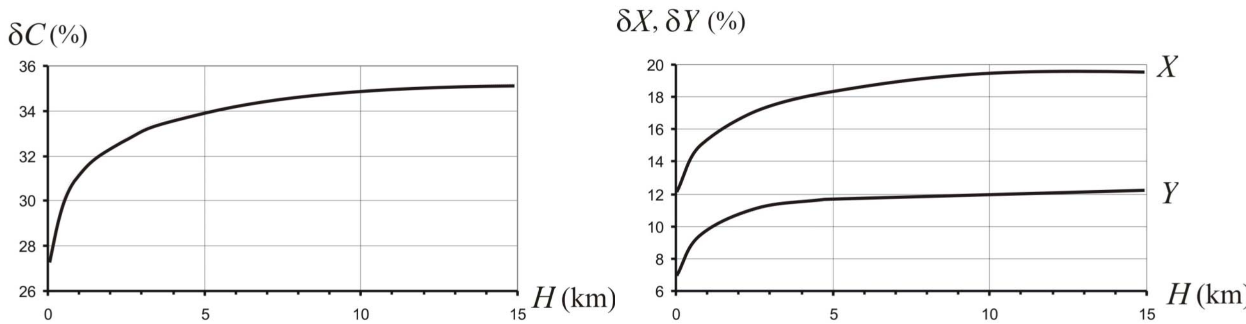


Figure 2. Images of the test object: A - initial image, C-distorted instantaneous image, B - corrected image.



A **B**

Figure 3. Average relative percentage error in estimating concentrations C, X, and Y as a function of sensor height above the sea surface.

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